Probing spin-charge separation using spin transport

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Pedagogical discussions are given on what constitutes a signature of spin-charge separation. A proposal is outlined to probe spin-charge separation in the normal state of the high T_c cuprates using spin transport. Specifically, the proposal is to compare the temperature dependences of the spin resistivity and electrical resistivity: Spin-charge separation will be manifested in the different temperature dependences of these two resistivities. We also estimate the spin diffusion length and spin relaxation time scales, and we argue that it should be experimentally feasible to measure the spin transport properties in the cuprates using the spin-injection technique. The on-going spin-injection experiments in the cuprates and related theoretical issues are also discussed.

1. Introduction

The normal state properties in the high temperature superconductors are anomalous in the context of the Fermi liquid theory. Two examples come from charge dynamics[1]: The electrical resistivity and inverse Hall angle have a linear and quadratic temperature dependences, respectively. For the optimally doped cuprates, such temperature dependences occur all the way to temperatures as high as about 1000 K. These anomalous properties suggest an unusual excitation spectrum. Precisely what are the elementary excitations, however, remains an open question.

One particular debate is whether or not spin-charge separation exists. Since the initial suggestion[2], considerable efforts have been devoted to interpret the existing experimental data using spin-charge separation based pictures. On the other hand, these data have also been analyzed without invoking spin-charge separation. Readers are referred to this proceedings for a snapshot of this continuing debate.

Theoretically, it is still not certain how spin-charge separation arises in specific models in two dimensions. The theoretical challenge is how to study in a controlled fashion the non-perturbative effects of electron-electron interactions, as it is known that the Fermi liquid theory is stable when interactions are treated perturbatively. The situation is different from one dimension, where the phenomenon of spin-charge separation was first discovered theoretically[3], as well as the opposite limit of large dimensions where metallic states with spin-charge separation have also been shown to occur in some specific models.

Instead of discussing these microscopic issues, here we address a phenomenological question: What would be (unambiguous) experimental signatures of spin-charge separation? In the remainder of this paper, we elaborate on what constitutes a signature of spin-charge separation, review a specific proposal of using spin transport as such a probe[4,5], and discuss the prospect of experimentally measuring spin transport as well as the status of some on-going spin injection experiments in the cuprates[6–9].

2. What is needed to probe spin-charge separation

Spin-charge separation is defined in terms of the excitations of a many-electron system. In essence, it says that A) there are two types of elementary excitations and B) the quantum numbers are such that, one elementary excitation has spin $\frac{1}{2}\hbar$ and charge 0 ("spinon") while the other has spin 0 and charge e ("holon"). More precisely, imagine we have solved all the many-body eigenstates of the 10^{23} or so electrons. Consider the many-body excited states whose energies are not very far above the ground state energy. Spin-charge separation describes the situation when it is necessary to introduce an elementary object

with spin $\frac{1}{2}\hbar$ and charge 0, *and* another with spin 0 and charge e, to reproduce the wavefunctions of these low-lying many-body excited states from the ground state wavefunction $|\mathrm{gs}>$. Namely, the many-body excited states have the general form $[A^\dagger_{\mathrm{holon}}]^l[A_{\mathrm{holon}}]^l[A^\dagger_{\mathrm{spinon}}]^m[A_{\mathrm{spinon}}]^n|\mathrm{gs}>$, where $A^\dagger_{\mathrm{holon}}$ (A_{holon}) and $A^\dagger_{\mathrm{spinon}}$ (A_{spinon}) create (annihilate) a holon and a spinon, respectively. In particular, the many-body states in the purely spin and charge sectors, $|$excited states I $>$ and $|$excited states II $>$, have to be separately constructed from the ground state,

$$\begin{aligned} |\text{excited states I} > &\sim [A^\dagger_{\mathrm{spinon}}]^n[A_{\mathrm{spinon}}]^m|\mathrm{gs}> \\ |\text{excited states II} > &\sim [A^\dagger_{\mathrm{holon}}]^n[A_{\mathrm{holon}}]^n|\mathrm{gs}> \end{aligned} \quad (1)$$

This definition parallels that for a Fermi liquid, where only a single species of elementary excitations is needed. Introducing $A^\dagger_{\mathrm{qp}}$ (A_{qp}) which creates (annihilates) a quasiparticle with both spin $\frac{1}{2}\hbar$ and charge e, we can write for all the low-lying many-body excited states,

$$\begin{aligned} |\text{excited states} > \;\sim\; & [A^\dagger_{\mathrm{qp}}]^n[A_{\mathrm{qp}}]^n|\mathrm{gs}> \\ & \text{for a Fermi liquid} \end{aligned} \quad (2)$$

In a Fermi liquid, Landau parameters are also needed to specify the residual interactions between these quasiparticles (as well as to create collective excitations out of the quasiparticles). Similarly, in a spin-charge separated metal, there are also parameters characterizing the residual interactions among the spinons and holons.

Following the above definition, we can now specify the basic elements of a signature of spin-charge separation. It should not only show the existence of two kinds of elementary excitations, but also provide the quantum numbers of these excitations. Namely, we need to know that one type of elementary excitations carry spin but no charge, while the other carry charge but no spin.

We comment in passing on the angle-resolved photoemission spectroscopy (ARPES), which has been extensively discussed in the literature in the context of spin-charge separation. In ARPES, a physical electron - containing both spin $\frac{1}{2}\hbar$ and charge e of course - is ejected. One doesn't know *a priori* whether any ARPES peak results from a) a convolution involving a coherent spinon, a coherent holon or both; b) a convolution involving other objects of exotic quantum numbers; or c) simply a quasiparticle-like excitation. From this perspective, ARPES does not directly tell the quantum numbers of the elementary excitations and, hence, doest not directly probe spin-charge separation. Further discussions along this line can be found in Ref. [10].

3. Probing spin-charge separation using spin transport

Such a proposal was made a few years ago[4,5]. The basic idea is as follows. Consider a spin current which will be generated by accelerating spins, and charge current generated by accelerating charges. We can infer that spin-charge separation exists if the carriers for the two currents are two separated excitations. Similarly, we can infer about the absence of spin-charge separation if the carriers for the two currents actually correspond to the same excitation. Our proposal is that, we can determine which is the case by comparing the temperature dependence of the spin resistivity with that of the electrical resistivity.

To see this, we first note that the spin resistivity can be defined in parallel to electrical resistivity. An electrical current, J, is established in the steady state when charges are accelerated by an electric field, E. The electrical resistivity is of course defined by the linear-response ratio

$$\rho = E/J \quad (3)$$

Similarly, a spin current, J_M, will be established when spins are accelerated by a magnetic field gradient, $\nabla(-H)$. The ratio

$$\rho_{spin} = \nabla(-H)/J_M \quad (4)$$

defines the spin resistivity. In a metal, the electrical resistivity ρ is proportional to the transport relaxation rate $1/\tau_{tr}$, which is the decay rate of the charge current. Similarly, ρ_{spin} is proportional to the spin transport relation rate $1/\tau_{tr,spin}$, the decay rate of the spin current.

In a spin-charge separated metal, spin current and charge current are carried by different elementary excitations. It then follows that the scattering processes and the corresponding scattering

phase space are in general different for the decay of spin current and decay of charge current. Therefore, the two resistivities will have different temperature dependences. We have calculated spin resistivities in models for spin-charge separation[4], with results which indeed follow the above general conclusions. One model is the Luttinger liquid[3] in which $\rho_{spin} \propto T^{\alpha_{spin}}$ and $\rho \propto T^{\alpha_{charge}}$, where the difference in the powers $\alpha_{spin} - \alpha_{charge}$ is non-zero and interaction dependent (for the one dimensional Hubbard model $0 < \alpha_{spin} - \alpha_{charge} < 2$). The other model is the U(1) gauge theory of the t$-$J model[11], in which $\rho_{spin} \propto T^{4/3}$ while $\rho \propto T$.

Consider next the case without spin-charge separation. Here the same quasiparticle-like excitations carry both the spin current and charge current. Any scattering process which causes the decay of one current will necessarily also lead to the decay of the other current. The two resistivities will then have the same temperature dependences, under three conditions; all these conditions are satisfied by at least the optimally doped cuprates. The conditions are a) spin fluctuations are not dominated by the ferromagnetic component; b) Fermi surface is large; and c) inelastic scattering dominates over elastic scattering. The conditions a) and b) have to do with the fact that in establishing a spin current the spin up and spin down excitations move in opposite directions. This leads to a matrix element for the decay of spin current that is slightly different from its counterpart for the decay of charge current. Conditions a) and b) guarantee that this difference in the matrix elements leads only to a difference in the numerical prefactors of the two resistivities, but not in their temperature dependences. Condition c) has to do with the possible fluctuating conductivities coming from fluctuating collective modes. In the clean limit specified by condition c), any fluctuating conductivity is better thought of as a drag contribution; a very general gauge invariance argument exists which guarantees that its temperature dependence is the same as that of the corresponding Boltzmann contribution. Unlike for a) and b), which are necessary, condition c) is sufficient but is in most cases not necessary. From neutron scattering results, we know that condition a) is satisfied for all cuprates. Condition b) is satisfied at least for the optimally doped cuprates, as can be inferred from the ARPES results. Finally, from charge transport data we can infer that condition c) is satisfied for most cuprates.

In short, the spin resistivity can be used to test spin-charge separation. Over the temperature range where the electrical resistivity ρ is linear in temperature, a non-linear temperature dependence of spin resistivity ρ_{spin} would imply spin-charge separation while a linear temperature dependence of ρ_{spin} signals the absence of spin-charge separation.

4. Experimental measurement of spin resistivity

While it is not easy to measure spin currents directly, the linear-response spin resistivity can be related to the spin diffusion constant D_s through the Einstein relation:

$$\rho_{spin} = 1/(\chi_s D_s) \tag{5}$$

where χ_s is the uniform spin susceptibility. There are a number of experimental techniques that can in principle be used to measure spin diffusion. One feasible means for the cuprates seems to be the spin-injection-detection technique[12].

The illustrative set-up can be found in Ref. [12], and also in Refs. [5,16]. Basically, a cuprate is in contact with either one or two ferromagnetic metal(s) (FM1 and in the latter case FM2 as well). An electrical current (I) is applied across the FM1-cuprate interface, injecting spins into the cuprates. In a steady state, the spatial distribution of the injected magnetization depends on the spin diffusion of the cuprates. The injected magnetization can be detected either by measuring the voltage induced across the cuprate-FM2 interface, or some alternative means.

To assess the feasibility of this kind of experiments, we need to estimate the spin diffusion length of the cuprates. For the normal state, we can relate the relaxation time for the total spin, T_1, to the relaxation time for the spin current, $\tau_{tr,spin}$, as follows,

$$1/T_1 \approx \lambda_{so}^2 (1/\tau_{tr,spin}) \tag{6}$$

where λ_{so} is the dimensionless spin-orbit coupling constant, which for the cuprates is of the order of 0.1. Note that this relationship is generally valid independent of the precise interactions responsible for the decay of the spin current and spin; λ_{so} measures the fraction of the interaction processes which lose the total spin. Combining Eq. (6) with the defining expression for the spin diffusion length, $\delta_{spin} = \sqrt{2D_s T_1}$, we derive the following relationship between the spin diffusion length and spin transport mean free path,

$$\delta_{spin} \approx (1/\lambda_{so}) l_{tr,spin} \tag{7}$$

From the above we have estimated the spin diffusion length in the normal state to be in the range of a thousand $\mathring{A}$ to a micron[4], long enough for spin-injection-detection experiments.

The recent spin injection experiments in the cuprates[6–9] became possible when perovskite manganites were used as the ferromagnetic layer(s). Presumably such manganite-cuprate heterostructures have much cleaner interfaces, since the two materials are structurally similar. So far the experiments are restricted to the superconducting cuprates. They have raised many interesting theoretical questions of their own, such as the physics of Andreev reflection[13–16] and the combined effects of Andreev reflection and single-particle transport on spin-injection characteristics[16] involving a ferromagnetic metal and a $d-$wave superconductor.

From the perspective of probing spin-charge separation, it is necessary to extend these experiments to the normal state and to carry out quantitative spin transport measurements. Note that only the linear response regime is needed for this purpose. As discussed in the previous section, what is needed is a plot of spin resistivity as a function of temperature. There are at least four possible ways to experimentally implement such a plot. a) The most rigorous is to extract the spin diffusion constant D_s from experiments which, through Eq. (5), provides the spin resistivity directly; b) Another possibility is to extract the spin diffusion length δ_{spin} from experiments. Eq. (7) implies that δ_{spin} is proportional to $l_{tr,spin}$ which, in turn, is proportional to the spin conductivity. The temperature dependence of $\frac{1}{\delta_{spin}}$ is then the same as that of ρ_{spin}; c) Along a similar line, it was shown[5] that the temperature dependence of ρ_{spin} can be directly inferred from the spin-dependent voltage V_s in a spin-injection-detection experiment. When the sample thickness d is small compared to δ_{spin}, ρ_{spin} is proportional to $I/(\chi_s V_s)$ where I is the injection current. In the opposite limit of $d \gg \delta_{spin}$, ρ_{spin} has the same temperature dependence as $\ln(I/\chi V_s)$; d) Finally, from Eq. (6), $1/T_1$ is proportional to the spin transport relaxation rate $1/\tau_{tr,spin}$ which in turn is proportional to the spin resistivity. The temperature dependence of $1/T_1$ is then the same as that of ρ_{spin}. There are experimental techniques - such as ESR - which can measure $1/T_1$ (or $1/T_2$) directly. Following Eq. (6) we estimate the ESR linewidth to be in the range of $3 - 30$GHz.

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